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Review Article

Sustainability Analysis of Decentralised Fibre-to-Fibre Scenarios – Reflecting the Amended EU-Waste Framework Directive - A Review

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Abstract:
This review examines whether chemical recycling based on the feedstock of cotton textile waste has the economic and sustainable potential to become established and compete with conventional fibres. In a sustainability analysis based on data of publications review, the resource consumption and potential environmental impacts of three recycling fibre scenarios (the Lyocell, the viscose and the cellulose-carbamate scenario) are quantified and compared with the fibres cotton, viscose and Lyocell. Recycled fibres tend to be more sustainable than conventional viscose, Lyocell and cotton.

Keywords: Fibre-to-fibre, Chemical recycling, Cotton, Viscose, Lyocell

1.0 Introduction:

In 2018, the European Waste Framework Directive was amended which obliges the member states to collect textile waste separately from 2025 onwards (EU, 2018). Waste textiles are increasingly seen as an important resource by politics and industry. Large quantity of textile waste coming from the fast-producing textile and clothing industry is a global problem. Moreover, the demand for textile fibres will triple worldwide by 2050 (Ellen MacArthur Foundation, 2017). The chemical recycling of waste textiles is hence becoming more relevant and is on the way to industrialisation. The recycling is seen as key enabler for a circular economy approach. However, little extensive data is published on current chemical recycling processes for cotton. This is due to the limited availability of industry-related data, as the processes are not yet applied on an industrial scale.
The main objective of this review is to examine whether chemical recycling based on pre-consumer or post-consumer cotton textile waste has the economic and sustainable potential to become established to compete with conventional fibres. Therefore, this review focusses on the environmental impact of three different recycled cellulosic fibre types - all using cotton textile waste as input - based on life cycle assessments (LCA).

2.0 Key Findings from the Review:

Fibre recycling is a suitable and sustainable method of recovering raw materials and saving resources. Recycled fibres tend to be more sustainable than their conventional equivalent. As the investigated processes are based on standard processes, it can be clearly seen that the carbamate process has an efficient conversion ratio of input to output mass with a rate of 1.25 The Lyocell and Viscose recycling scenarios produce the same quality by not using virgin raw materials. Optimisations of all recycling processes are necessary for economically successful textile recycling. There is a lack of detailed LCAs of chemical fibre-to-fibre recycling processes with published primary inventory data.

3.0 Comparison of (semi-) industrial recycling processes of cotton, viscose and Lyocell

3.1 Methods

The method applied consists of two steps, literature review (2010 - 2020) of freely available publications, and data preparation in form of different scenarios to be analysed based on a LCA in order to compare them with each other. These approaches are described hereafter briefly.
First, research was conducted on the topic of chemical textile recycling. Publications in German and English from the last ten years were considered. A search with the following keywords was conducted on the academic databases *Research Gate, ScienceDirect, Google Scholar,*

Mendeley and SpringerLink: textile recycling, recycled fibre, chemical recycling of textiles, cotton recycling, lyocell recycling, viscose recycling, LCA of recycled fibres. Based on the title, most of the publications could already be excluded because the fibre types did not match the scope of the analysis. After reading the summary further publications were excluded, as relevant process parameters, such as the fibre type (predominant part cotton) and the type of recycling (chemical recycling) were not fulfilled. Finally, 7 publications - Kazan et al. (2020), Paunonen et al. (2019), Spathas (2017), Schultz & Suresh (2017), Oelerich et al. (2017), Jewell (2017) and Shen & Patel (2010) - were considered as relevant, which met the requirement being conducted according to ISO 14044:2016. In addition to the academic publications, websites of companies and European research projects were reviewed.

Secondly, the framework of sustainability analysis was defined: system boundary, data and literature used, functional unit, assessment criteria and assumptions as well as limitations of the analysis were determined and defined, based on the relevant literature. The sustainability analysis was carried out based on the data from the publication review in order to evaluate and compare the results of the recycling scenarios with the reference fibres. To validate the results, expert-feedback-interviews with three process experts from the fields of science, start-up and business were conducted.

3.2 Sustainability analysis framework

The analysis of the potential environmental impacts of the recycling fibres is carried out applied by LCA based on defined assessment criteria. The data used is taken from the reviewed publications. The system boundary of the sustainability analysis includes the processes from cradle to gate. This means that all production steps, starting from the raw material of the pre-sorted used textiles to the spun fibre, are included and analysed. Collection and sorting as preceding steps were excluded.

The two main recycling processes are pulp and fibre production. The main input resources include energy, chemicals and water. The use of resources in the process steps result in resource consumption and environmental impacts, air and water emissions as well as waste and by-products. The main raw material to produce recycled fibres is pre-sorted used textiles, consisting mainly cotton. For used textiles as input raw material no impacts are calculated. All data is normalised to the functional unit of 1,000 kg of fibre output. The impact categories are based on the standard material flows and impact categories for LCA of textiles. The impact categories are input mass, energy, water, chemicals, climate change potential and land consumption. The scope includes three recycling scenarios: the Lyocell, the viscose and the cellulose-carbamate scenarios. To be able to evaluate the investigated recycling scenarios more comprehensively, a comparison with reference fibres is to be conducted. The selected reference fibres are cotton, conventional viscose and Lyocell fibres. Since all three fibres share the basic component cellulose and have comparable fibre properties, the recycled fibres can be seen as an alternative to conventional fibres.

3.3 Results, evaluation and comparison of the recycling scenarios

The results from the assessment of the individual recycling scenarios are compared with each other as well as with the conventional reference fibres. Table 2 provides an overview of the results from the assessments of the recycling scenarios. The values listed in the table are the calculated average potential resource consumptions and the resulting environmental impacts for each scenario referenced to 1,000kg recycled fibre output. The values should only be seen as reference values for assessing the sustainability of the scenarios. The comparability of the scenarios is partially limited, as the study parameters are not identical even though the reviewed publications perform according to ISO 14044.

The conversion ratio of input to output mass of the carbamate process is the most efficient one with a rate of 1.25 (Paunonen et. al., 2019). Depending on the quality of the raw material, front-to-back-yield (FTBY) can almost be one to one. A further advantage is that the recycled fibres can be recycled several times and can thus be returned to the material cycle (Fashion For Good, 2020a). Since no agricultural land is required for raw material production, the recycling scenarios score best in this category. Compared to virgin fibres the recycled ones have the benefit that the raw material textile waste has little or no impact on the LCA as textile waste is already available. With regards to the water consumption, the Lyocell and the carbamate scenario are on a comparable level with approx. 30,000 litres. The Lyocell scenario indicates that both recycled and conventional fibres have the lowest water consumption (Oelerich et. al., 2017; Schultz & Suresh, 2017). The Lyocell process is an almost closed process. The solvent can be nearly completely recovered; thus, the process water can be reused. The results of the carbamate scenario show that an integrated process with an optimised water circuit can almost save two thirds of the water, in contrast to sequential processes without recirculation (Paunonen et.al., 2019).

Table 2: Scenario comparison (per 1,000kg recycled fibre output)

Resource Category	**Unit**	**Recycling Scenarios**		
		Lyocell*	**Viscose**	**Carbamate**
Input raw material	kg	2,600**	2,400**	1,254
Energy	kWh	1,035	6,890	9,444
Water	l	15,000	135,720	29,824
Caustic Soda	kg	16	-	223
Climate Change (Carbon Footprint)	kg CO_2 eq.	4,250**	3,189	1,979
Land consumption	m^2/t	10	-	-

*only Pulp Production covered, **assumptions out of the conventional spinning process within the reference Lyocell process

The comparison of chemical consumption is complex because the chemicals used vary depending on the process. Nevertheless, the results show that the use of chemicals and especially the production of chemicals have a large contribution to the environmental impact of the fibres (Schultz & Suresh, 2017). Among the recycling scenarios, the Lyocell scenario is the best in terms of chemicals. The general consumption of chemicals is low, and the solvent used is non-toxic and can be almost completely recovered (Oelerich et. al., 2017). In terms of chemical use, the carbamate scenario is to be classified between the Lyocell and viscose scenario. The carbamate process substitutes the harmful chemical carbon disulphide with urea, the processes remain identical, and the general consumption of chemicals is comparable high (Paunonen et.al., 2019).

The processes of pulp and fibre production are energy-intensive, especially the spinning process. The review of the scenarios is limited due to the lack of data within the Lyocell scenario. The carbamate scenario shows that by integrating pulp and fibre production processes, resources can be saved (Paunonen et. al., 2019). An integrated process approach safeguards the production in one facility.

3.4 Discussion

The findings of this review identify the ecological potential of recycled fibres. It is shown that recycled fibres have the potential to be process-wise and with focus on raw material more sustainable than conventional viscose, Lyocell and cotton fibres due to their lower resource consumption and consequently lower environmental impact. The Lyocell process, in particular, can be classified as ecologically harmless. The viscose scenario scores in all categories lower than the other two recycling scenarios. However, recycling is dependent on the preceding steps of collection and sorting. When designing new textile products, the recyclability of the product (product design for recycling) or the afterlife handling should already be considered.

Since the quantities of used textiles collected in the EU are increasing and will continue to increase from the mandatory separate collection in 2025, fibre-to-fibre recycling plants should be located in the area of the collected textile waste in future.

In general, it can be stated that process optimisation such as the recovery of chemicals, the recirculation of process water and the generation of synergies through integrated plants have a positive effect on LCA. This applies to recycling as well as for conventional processes.

To conclude, the substitution of conventional fibres with recycled ones from textile waste offers a great opportunity to reduce the global negative environmental impact of textile production. Optimisations of all recycling process steps are necessary to improve the economy of textile recycling.

4.0 Recommendation for future work

The review has identified gaps in literature. There is a need for publication of inventory data and detailed studies. Further quantitative data are necessary regarding energy consumption, chemicals consumption, FTBY and waste (fibres, chemicals), which will allow a direct comparison of the systems. As long as the cost for new materials and the costs for waste are lower than their recycled materials, the systems will not be competitive at all. Furthermore, it would be worth to include the same data during recycling of the recycling-chemicals to close their loop, too.

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